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Magnetic properties of Co-W thin films

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Abstract. In this paper, the magnetic properties and structure of the Co-W films of different compositions prepared by magnetron sputtering on glass substrates without and with Ta or Ru buffer layers were investigated. The dependences of coercive force on the W content for the studied films were non-monotonic. The peak value of the coercive force of about 400 Oe was observed for the films on glass and Ta layers with W content of 8-9 at. %. The films deposited on Ru layers had a coercive force of 4 times less, and it was practically independent of the W content in a wide range from 6 to 20 at. %.

1. Introduction

Purposeful modification of the properties of natural magnets is one of the priority areas of research in modern materials science. Among the specific tasks of this direction is to increase the magnetic anisotropy and the level of magnetic hysteresis, which are in demand in the development of materials for permanent magnets, media with super-dense recording of information, magnetic sensor elements. This problem is solved, in particular, in the framework of binary systems Co-M, where M – elements characterized by effective spin-orbital coupling and actively affecting the electronic structure of Co [1-6]. Typical examples of such elements are Mo [7], Pt [8], W [2]. The Co-W system is particularly interesting by the presence of phase separation [9]. It allows you to isolate the crystal grains of the strongly magnetic phase at the expense of the weak-magnetic interlayer phase and thus realize the process of magnetization reversal close to coherent rotation of magnetization. In the literature, there is some information about the structure and properties of Co-W films obtained by electrochemical deposition [10] or sputtering [11]. This information allow to conclude that an important factor affecting the characteristics of relatively thin films is the structuring effect of the substrate. This work is devoted to a comparative study of the magnetic properties of the Co-W films deposited directly on a glass substrate and Ta or Ru buffer layers characterized by a body-centred cubic and hexagonal crystal structure, respectively.

2. Experimental details

The film samples of $\text{Co}_{100-x}\text{W}_x$ system were obtained by magnetron co-sputtering of Co and W single-component targets. The cover glasses (Corning) were used as substrates. The films were deposited directly on a glass surface (samples of A type) or on the same substrates covered with Ta (samples of B type) or Ru (samples of C type) buffer layers of 5 nm thickness. The formation of all layers was carried out in Ar atmosphere at the pressure of $2 \cdot 10^{-3}$ Torr in the presence of a homogeneous magnetic



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field of 250 Oe in the substrate plane at a speed of about 0.1 nm/s. The thickness of the Co-W layers was 40 nm. The variance of the composition in the Co-W layers was realized by changing the deposition rates of metals due to the corresponding regulation of the ratio of electric power supplied to the targets. Control of the total thickness of the film samples was carried out by means the Dektak 150 surface stylus profiler. The composition of the layers of Co-W was determined by means Nanohunter using X-ray fluorescence spectroscopy. X-ray diffraction of some selected samples was performed by means D8-Advance diffractometer. The automated vibrating sample and magneto-optical Kerr Evico Magnetism magnetometer were used for the study of the magnetic properties of the films.

3. Results and discussion

The effectiveness of influence of non-magnetic impurity on the magnetism of ferromagnetic metals is primarily characterized by the concentration dependence of spontaneous magnetization (M_s). Figure 1 shows such dependences measured at room temperature for the $\text{Co}_{100-x}\text{W}_x$ films deposited directly on a glass substrate and Ta or Ru buffer layers. It can be seen that the introduction of tungsten into the film in the range of $0 \leq x < 30$ at. % causes a sharp and almost linear reduction of M_s which occurs in the same way in samples of different types and is drastically than it would be with a simple dilution of a ferromagnetic. The first indirectly indicates the absence of noticeable mixing between the buffer and main layers, and the second – a strong hybridization of 3d and 5d electronic subsystems of Co and W, leading to a decrease of the average magnetic moment on the Co atom. Thus, it can be concluded that the used technology of magnetron co-sputtering leads to a sufficiently effective mixing of sputtered components and forms a binary film macroscopically homogeneous in the elemental composition.

Figure 2 shows the diffraction patterns of the Co pure films of different types, measured in $\text{Cu}_K\alpha$ radiation. Presented data testify that the presence and the material of the buffer layer has a certain influence on the structure of the ferromagnetic layer. Films of A type (curve 1) demonstrate the presence of weakly expressed diffraction maxima in the corners, allowing these maxima to be associated with reflections from the planes of type (100) and (002) hcp crystallite lattice. The same two peaks are typical for films of B and C types (curves 2 and 3), but their intensity is much higher. The considerable width of these peaks and the absence of other diffraction lines characteristic of polycrystalline Co indicate the fine state of the films and the presence of a certain crystalline texture. Summarizing all these data, it can conclude that the role of buffer layers is reduced mainly to

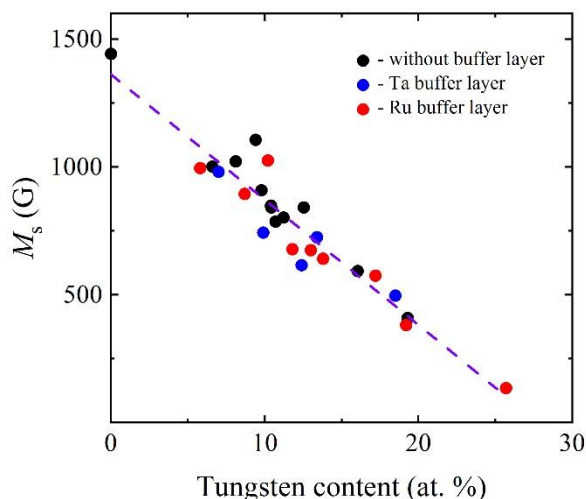


Figure 1. Saturation magnetization for $\text{Co}_{100-x}\text{W}_x$ films deposited directly on a glass substrate and Ta or Ru buffer layers.

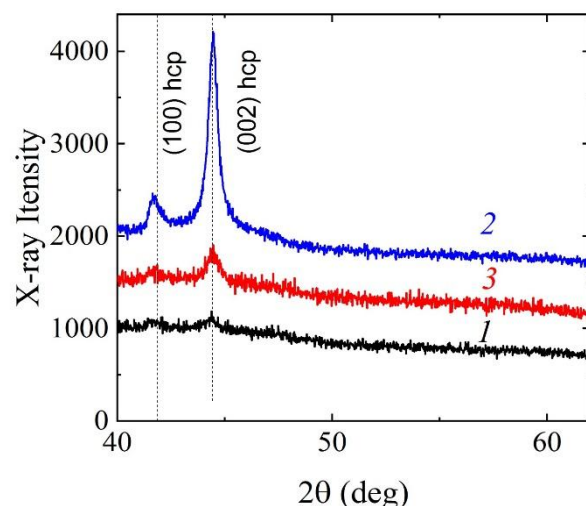


Figure 2. Diffraction patterns of Co films deposited on a glass substrate (1), Ta (2) or Ru (3) buffer layers.

texturing. In this respect, the films on Ta layers behave most effectively, the texture of the film on Ru layers is less pronounced and it is quite weak in the samples deposited directly on the glass. Moreover, in all these cases, the average size of crystallites is approximately the same. The size of the crystallites in the films estimated by the Scherrer formula is 15-20 nm.

Information about the hysteresis properties of the studied films was obtained from the analysis of hysteresis loops measured in the plane of samples along the axis of technological magnetic field. Figure 3 shows examples of typical magnetometric loops for the films with different content of tungsten. It is seen that in the absence of impurity (Figure 3, *a*) the change of magnetization occurs abruptly. This is typical for 3d metal films with uniaxial magnetic anisotropy, which is formed when the films are deposited in a magnetic field. However, the introduction of tungsten in the concentration of 7-12 at. % leads to a sharp change of the shape of the loop (Figure 3, *b*). On the loop, it is possible to determine three sections of a comparable change in the magnetization. Two of them characterize a smooth variation of magnetization in the region of relatively strong magnetic fields and one sharp change of M_s in near the coercive force. This form of the loop, most likely, indicates the transition of the film in the so-called "trans-critical state", which in the absence of an external magnetic field is represented as a set of micro domains with non-collinear magnetic moments [12]. The existence of a "trans-critical state" in turn reflects the presence of a significant perpendicular magnetic anisotropy in the sample, which is comparable in magnitude to the anisotropy of the shape. The latter allows us to estimate the level of the perpendicular anisotropy constant as 5×10^6 erg/cm³.

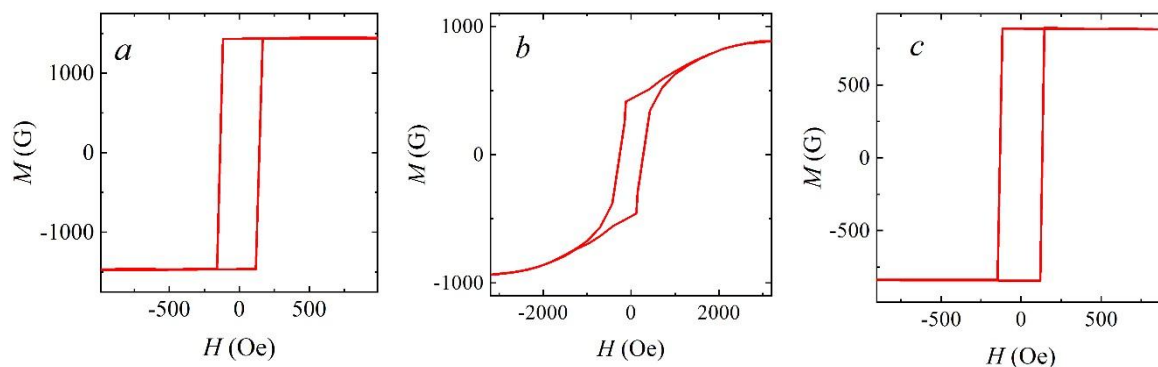


Figure 3. Magnetometric hysteresis loops of $\text{Co}_{100-x}\text{W}_x$ films deposited on glass substrate for the different concentrations of tungsten: *a* – 0; *b* – 10; *c* – 13 at. %.

Increasing the W concentration to 13 at. % leads to the inverse transformation of hysteresis loop (Figure 3, *c*), which indicates a significant decrease in the perpendicular anisotropy. Typically, perpendicular magnetic anisotropy in thin films obtained by the sputtering is associated with a specific microstructure. The latter is a set of columnar formations of the strong magnetic phase, separated by layers with reduced magnetization. In this regard, a very sharp concentration change perpendicular to the magnetic anisotropy is unusual and requires more detailed study.

Figure 4 (curve 1) shows the dependence of coercive force (H_c) on composition for the films deposited directly on a glass substrate. It quantitatively illustrates the changes in the hysteresis properties described above and, in particular, indicates a more than 100-multiple decrease of H_c in the narrow concentration range of $11 < x < 13$ at. % W, as well as the realization of the anomalous low values of the coercive force ~ 1 Oe at $x > 13$ at. % W. Such dependence of $H_c(x)$ indirectly indicates radical transformations in the microstructure of Co-W films, the identification of which requires more detailed structural studies. The dependences of $H_c(x)$ for films deposited on different buffer layers are also shown in Figure 4. It is seen that the films on Ta (curve 2) demonstrate qualitatively similar behavior of the coercive force. The dependence of $H_c(x)$ for films on Ru (curve 3) behave differently. In these films, the introduction of W also leads to an increase of coercive force, but it is not so pronounced and extends to a much larger range of W concentration. The hysteresis loop of the film

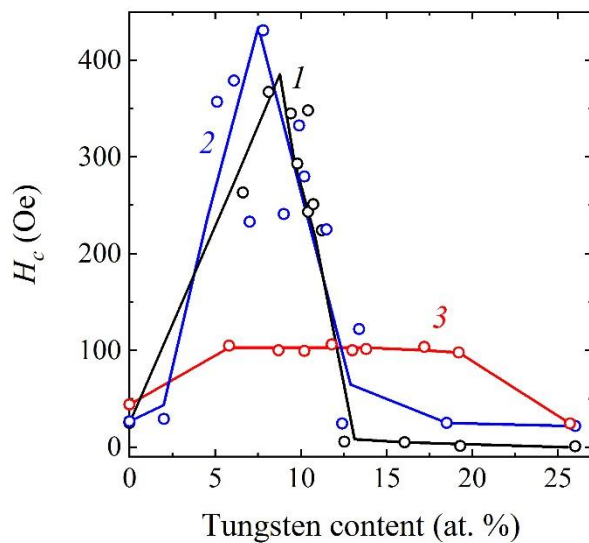


Figure 4. Concentration dependences of coercive force for $\text{Co}_{100-x}\text{W}_x$ films deposited directly on a glass substrate (1) and Ta (2) or Ru (3) buffer layers.

deposited on Ru layers does not have any characteristic features, both at a given concentration W and in the entire interval of the existence of the magnetically ordered state.

The marked difference is also present in the form of hysteresis loops. The hysteresis loops of three types of samples with a concentration of W of about 10 at. % are shown in Figure 5. The hysteresis loops of the films of A and B types are similar and correspond to the "trans-critical state". The hysteresis loop of the films of C type does not have any characteristic features both at a given concentration W, and in the entire region of existence of the magnetically ordered state. Interestingly, the character of the crystal structure of the pure Co films of all three types are the same. It follows that the material substrate has a different effect on the process of structural transformations occurring when adding tungsten. Probably, the Ru buffer layer which hcp crystal lattice as like cobalt, exists in closer relationships with the ferromagnetic layer and to some extent blocks the structural changes of the latter.

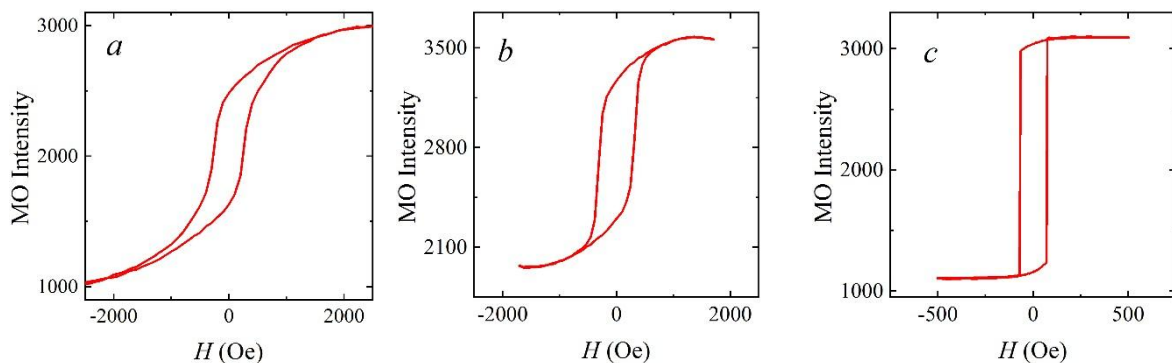


Figure 5. Magneto-optical hysteresis magneto-optical loops of $\text{Co}_{90}\text{W}_{10}$ films deposited directly on a glass substrate (a) and Ta (b) or Ru (c) buffer layers.

4. Conclusions

The study shows that the introduction of tungsten leads to a significant modification of the magnetic properties of the Co films. The result of doping can be both the formation of perpendicular magnetic anisotropy in the films and a significant increase in the level of magnetic hysteresis, and the realization of a magnetic soft state. The concentration areas and quantitative characteristics of these effects vary considerably when using buffer layers with different types of crystal structure.

Acknowledgments

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